Patent Application

of

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for

Method for Fabricating Zig-Zag Slabs for Solid State Lasers

GOVERNMENT SPONSORSHIP

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FIELD OF THE INVENTION

The present invention relates to a method for fabricating slab media for solid state lasers and in particular to a method for fabricating large numbers of slabs supporting zig-zag propagation of light therethrough.

BACKGROUND OF THE INVENTION

Solid state lasers have been found very useful for generating high power laser beams. A typical solid state laser has two main parts: a solid state laser medium and a pump source. The pump source can be another laser or array of lasers, an arc

lamp, a flashlamp or some other suitable source of illumination. The solid state laser medium is typically a slab of material doped with appropriate active lasant, e.g., an active ion such as Nd, Er, Yb, Tm, Ho, etc.

Recently, slabs constructed to permit light to travel along a zig-zag path have gained popularity because of their ability to reduce thermal effects experienced by the slab during laser operation. Specifically, during high average power operation solid state lasers experience local refractive index variations, thermal lensing and stress birefringence of the slab. The geometry and further improvements to the zig-zag slab laser have addressed these problems and have helped to overcome the optical beam distortion due to these thermal effects. For more information about zig-zag slabs for solid state lasers the reader is referred to U.S. Pat. No. 4,894,839 to Baer; U.S. Pat. No. 5,479,430 to Shine, Jr., et al. and to U.S. Pat. No. 6,134,258 to Tulloch et al.

As slabs permitting zig-zag beam propagation have gained popularity, the technical challenge has shifted to fabrication methods. The doping of the slab can be achieved by a number of known approaches, including the Czochralski growth method, which is particularly well-suited for making slabs of YAG doped with Nd (Nd:YAG lasers). In order to achieve high power operation an optimal doping concentration balancing optical gain with optical loss is desirable. A method for achieving high active ion concentrations is described in U.S. Pat. No. 6,014,393 to Fulbert et al., as well as the other related applications. More

specifically, Fulbert teaches how to achieve base material doping levels such that the ion concentration is equal to or higher than 2%. Further, recent research into lasers based on poly-crystalline host materials (i.e., ceramics) has led to Nd^{3+} dopant ion concentrations of around 10% in YAG.

The numerous advantages of zig-zag slab lasers are counterbalanced by the difficulties encountered in their manufacture. The prior art teaches several aspects of the manufacturing process of zig-zag slabs in U.S. Pat. Nos. 6,377,593; 6,472,242 and 6,566,152 all to Peterson et al.

The prior art also teaches which portion of the slab should be doped by Injeyan et al. in U.S. Pat. Nos. 6,094,297 and 6,256,142.

In addition, the prior art even teaches how to appropriately integrate elements into the slab - for example half/quarter wave plates - see the published patent application U.S. Patent Application 2002/0171918 to Clapp.

These prior art references teach how to build a zig-zag slab for use as laser or amplifier, however, the techniques disclosed are not suitable for batch processing. More particularly, they are not well-suited for rapid and low-cost manufacture of a large number of slabs for solid state lasers. This is especially true for cases where the performance and doping have to be well controlled and very good performance of the slab lasers is a requirement.

OBJECTS AND ADVANTAGES

In view of the shortcomings of the prior art, it is a primary object of the present invention to provide a method for fabricating a large number of slabs that can be used in solid state lasers. More specifically, it is an object of the invention to provide a method for batch manufacturing of such slabs and in such a manner that the improved performance characteristics of slabs are retained.

It is also an object of the invention to ensure that the process of manufacture is easy to implement and cost effective.

These and numerous other objects and advantages of the present invention will become apparent upon reading the following description.

SUMMARY

In one embodiment the present invention includes a method for efficiently producing a large number of zig-zag slabs that can be used in solid state lasers. The method calls for providing two non-active media and an active medium. A medium as used herein includes glasses, ceramics, single-crystal materials and polycrystalline materials. The non-active media are typically undoped optical media. The active medium is typically the same material as the non-active media but it is doped with an active ion, such as ions of Nd, Yb, Er, Tm, Ho, etc. The two non-active media are bonded at two opposite faces of the active medium to produce a slab sandwich. The slab sandwich has

coupling faces, i.e., faces through which light can be in- and out-coupled on the non-active media. The length of the slab sandwich is defined between the coupling faces and its width and thickness are defined along the two orthogonal directions.

The slab sandwich is diced approximately perpendicular to its thickness to produce slab slices. The slab slices have parallel surfaces coextensive with the length of the slab sandwich. These surfaces are rendered to obtain two total-internal-reflection (TIR) surfaces. The distance between the TIR surfaces defines a thickness of the slab slice. The slab slices are diced along a direction approximately perpendicular to the two total-internal-reflection surfaces and approximately along the length to produce a number of zig-zag slabs.

The method of invention admits of numerous embodiments. In one embodiment the bonding of non-active and active media is performed by diffusion bonding. In another embodiment the bonding is achieved by silicate bonding, as taught in US patents 6,548,176, and 6,284,085. In still another embodiment the bonding is achieved by frit bonding.

The rendering step can include an initial dicing of the slab sandwich along a plane substantially parallel to the two TIR faces. Preferably, the initial dicing is performed to ensure that the thickness of the slab slice is precisely controlled. In a preferred embodiment, the initial dicing is performed to achieve a thickness in the range between 0.01 and 20. mm.

Furthermore, the rendering step typically includes polishing the two parallel surface as well as coating them.

The coating on the TIR surfaces is preferably designed to permit TIR of the propagating laser beam, while preventing contamination of the TIR surfaces which induces scatter and absorption loss. For example, Teflon coatings were applied to TIR surfaces of face-pumped slab lasers to protect TIR surfaces from contamination by cooling water in US 5,479,430. More recently, SiO_2 coatings have been used, as taught by Tulloch et al., in US 6,134,258. It is further preferable for the TIR surface coatings to provide high loss (i.e., low reflectivity) for light incident at less than the critical angle for TIR, since some fraction of the amplified spontaneous emission (ASE) or spontaneous emission (SE) is incident at angles less than the TIR critical angle. Finally, in cases where the slab is optically pumped through the TIR surfaces, it is preferable for the TIR surface coatings to provide low transmission loss at the pump wavelength.

The coupling faces are also processed. In some embodiments the coupling faces are polished. In other embodiments the coupling faces are diced and polished to predetermined angles. These angles will typically be different and will correspond to the angles desired for in- and out-coupling of light during operation. Furthermore, in any of these embodiments the coupling faces can be anti-reflection coated to reduce light losses.

The side walls of diced zig-zag slabs are preferably treated to further improve the confinement or retention of pump and generated light within the zig-zag slabs while promoting the loss of SE and ASE. In some embodiments this is achieved by roughening of at least one and preferably both side walls. The roughening can be controlled and parametrized such as to produce a certain amount of forward scatter of pump light in the zig-zag slab. In alternative embodiments the sidewalls can be polished to an appropriate degree and coated with materials whose index of refraction is chosen to channel the pump radiation into the slab but transmit the ASE out of the slab.

A detailed description of the invention and the preferred and alternative embodiments is presented below in reference to the attached drawing figures.

BRIEF DESCRIPTION OF THE FIGURES

Fig. 1 illustrates the selection of active and non-active media according to the method of invention.

Fig. 2 is a view of a slab sandwich produced from two non-active media and an active medium.

Fig. 3 illustrates the dicing of the slab sandwich of Fig. 2 into slab slices.

Fig. 4 is a view of a slab slice.

Fig. 5A&B are plan side views illustrating the coatings applied to the slab slice of Fig. 4.

Fig. 6 illustrates the dicing of a coated slab slice into zig-zag slabs.

Fig. 7 shows a portion of a zig-zag slab with treated side walls.

Fig. 8A&B illustrate alternative embodiments of the method.

DETAILED DESCRIPTION OF THE EMBODIMENTS

In accordance with the invention a number of zig-zag slabs for use as solid-state lasers or laser amplifiers are manufactured from two non-active media **10, 12** and an active medium **14,** as shown in Fig. 1. Non-active and active media **10, 12, 14** preferably use the same host material. In the present embodiment the host material is YAG. In alternative embodiments host materials such as glass, poly-crystalline ceramics, or single-crystal materials can be used.

To provide optical gain, active medium **14** is doped with a lasant. The lasant can be an active ion such as Nd, Er, Yb Tm, Ho, etc. In the present embodiment, the lasant in active medium **14** is Yb and the doping level is 10%.

Preferably, media **10, 12, 14** initially have the shape of parallelepipeds with flat surfaces for bonding non-active media **10, 12** at two opposite faces **16, 18** of active medium **14.** Non-active medium **10** is bonded with face **20** and non-active medium **12** is bonded with face **22.** The bonding process results in a slab sandwich **24** as shown in Fig 2. The dimensions of media **10, 12, 14** are selected in advance such that bonded slab sandwich **24** has a requisite length L, width W and thickness T to allow for production of a desired number of zig-zag slabs after polishing and dicing, as described below.

The bonding process for bonding surfaces **20, 18** and **16, 22** can be any suitable process that produces an optical interface between the bonding surfaces. At least three methods including diffusion bonding, silicate bonding, and frit bonding are suitable for this purpose.

In accordance with the diffusion bonding method, bonding surfaces **20, 18** and **16, 22** are joined together to make one composite structure by first bringing them into optical contact to form an assembly. The assembly is then heated to a temperature on the order of the melting temperature of the host material, and interdiffusion of material at the two interfaces causes bonding. One of the advantages of diffusion bonding is that no glues or other agents are required for bonding media **10, 12, 14**. On the other hand, the method requires holding media **10, 12, 14** at elevated temperatures frequently in excess of 1,000 °C for many hours. Diffusion bonding is known in the art, for example, as described in U.S. Pat. No. 5,441,803.

In accordance with the silicate bonding method a solution of NaOH and SiO_2 in water as the bonding agent is applied in the interfaces between surfaces **20, 18** and **16, 22** after these surfaces are polished and cleaned. A precise amount of the solution is applied to one of the surfaces to be bonded and then the surfaces are quickly joined. Typically, the bond begins to set within seconds. One of the advantages of this approach is that it is not time-intensive and is low-cost. For more

information on this bonding method the reader is referred to US Patents 6,548,176, and 6,284,085.

The frit bonding method is known in the art and is typically used when the host material is a glass or a ceramic. In this method, ceramic powder is used as a frit between two surfaces to be bonded followed by heating to nearly the melting point to provide bonding.

In the present embodiment diffusion bonding is applied to create slab sandwich **24**. Once complete, the interfaces between surfaces **20, 18** and **16, 22** delimiting the doped and un-doped regions of slab sandwich **24** are inspected to ensure that they are free of defects. A person skilled in the art will realize that various routine preliminary tests of slab sandwich **24** can be performed to ensure that its quality is sufficiently high to warrant continued processing. For example, a strength test can be applied to ascertain the force required to break the bond. The strength of the bond gives an indication of the amount of thermal stress the slab can handle during operation.

Non-active media **10, 12** provide coupling faces **26, 28** at two opposite ends of slab sandwich **24**. Length L of slab sandwich **24** is defined as the distance between coupling faces **26, 28,** as shown in Fig. 2. Width W and thickness T of slab sandwich **24** are defined along the two directions orthogonal to length L.

Fig. 3 illustrates the next step during which slab sandwich **24** is diced substantially perpendicular to thickness T to produce a

number of slab slices **30**. Each one of slab slices **30** is cut to a thickness t while retaining width W and length L. Two parallel surfaces **32, 34** (shown on Figure 4) coextensive with length L are rendered to produce total-internal-reflection (TIR) surfaces. The rendering includes polishing since the dicing performed in the previous step leaves TIR surfaces **32, 34** with an undesirable degree of roughness. The polishing step should be precise enough to control thickness t of slab slice **30** to within +/- 0.01 mm. In most cases final thickness t of slab slice **30** corresponds to the thickness of the zig-zag slab and is selected in the range between 0.01 mm and 20 mm.

Fig. 4 illustrates further processing of one of slab slices **30**. After dicing of the slab sandwich **24** slab slices **30** have coupling faces **36, 38** that are segments of coupling faces **26, 28** originally defined in slab sandwich **24**. Coupling faces **36, 38** are processed to adapt them for in- and out-coupling of light that will be propagating through zig-zag slabs and to adjust the total length of zig-zag slabs based on the lengths of undoped and doped regions through which the light is to propagate. The processing of coupling faces **36, 38** thus includes cutting and polishing of coupling faces **36, 38** to produce certain angles α, β also referred to as apex angles in the art. In Fig. 4 the length of slab slice **30** has been reduced from L to S and coupling faces **36, 38** have been polished at apex angles α and β respectively. In fact, the side cross-sectional view of processed slab slice **30** is analogous to that of a finished zig-zag slab as described below.

In addition to dicing and polishing, slab slice **30** is also coated as shown in the side views of Figs. 5A&B. In particular, rendering of TIR surfaces **32, 34** preferably includes providing at least one of them, and preferably both, with a coating **40** to improve retention of laser light and/or to increase loss of undesired light such as ASE and other spurious light. Such coatings are either single-layer or multi-layer coatings.

In addition to protecting TIR surfaces **34** from contamination, coatings **40** can optionally provide improved optical performance in two distinct and independent ways. A first function of coatings **40** is to increase loss for light at the operating wavelength of the laser that is incident on the TIR surfaces **34** at less than the critical angle for TIR. Since some of this light is SE or ASE, coupling it out of the laser slab is desirable. For example, a coating providing a reflectivity of less than 1% for light at the operating wavelength of the laser that is incident on TIR surfaces **34** from within the slab at angles less than about 0.9 times the TIR critical angle is a suitable coating for this purpose. A second function of coatings **40** is to provide high transmissivity for light at a pump wavelength and incident on coatings **40**. Such a coating design is beneficial in cases where optical pumping is performed through TIR surfaces **34**. For example, a coating providing a reflectivity of less than 1% for light at a pump wavelength that is incident on TIR surfaces **34** from outside the slab at angles less than about 45 degrees is a suitable coating for this purpose. Design of single-layer and multi-layer coatings for

such purposes, either independently or in combination, is known in the art.

Fig. 5B shows a coating **44** deposited on coupling faces **36, 38.** Coating **44** is a single-layer or multi-layer coating as described above, designed to have minimal transmission loss at the laser operating wavelength. In some cases, where optical pumping is performed through coupling face **36** and/or coupling face **38,** coating **44** is also designed to provide low transmission loss at the pump wavelength.

Fig. 6 illustrates the dicing of coated slab slice **30** into individual zig-zag slabs **48.** Slab slice **30** is diced approximately perpendicular to TIR surfaces **32, 34** and along the length S of slab slice **30.** After dicing each zig-zag slab **48** has two side walls **50, 52** defining a zig-zag slab of width w. Side walls **50, 52** exhibit a surface roughness as dictated by the dicing process. At this point zig-zag slab **48** can be used as a laser or amplifier.

It is preferable, however, that zig-zag slabs **48** undergo further treatment. In particular, side walls **50, 52** of each zig-zag slab **48** should be treated to adjust surface roughness and other surface properties, as illustrated in Fig. 7. Fig. 7 shows only a portion of zig-zag slab **48** as well as laser light **54** and pump light **56** propagating through it. In this embodiment side walls **50, 52** are further roughened in order to promote losses through side walls **50, 52** and thus decrease SE and ASE produced at the wavelength of laser light **54.** Of course, losses of SE and ASE

through side walls **50, 52** also promote the loss of pump light **56.** The roughening can be controlled to achieve a certain amount of forward scatter of pump light **56** into zig-zag slab **48** and thereby control its loss. A person skilled in the art will appreciate that the loss of pump light has to be balanced with the advantages of reduced SE and ASE. In some embodiments increasing the intensity of pump light **56** or side pumping can be used in accordance to well-known practices. In still other embodiments side walls **50, 52** can be polished rather than roughened. In these embodiments confinement of pump light **56** is improved but SE and ASE are typically increased.

Figs. 8A&B illustrate several alternative embodiments of the method. Fig. 8A illustrates a slab sandwich **80** in which an active medium **82** is treated and polished at angles δ and γ prior to attaching two non-active media **84, 86.** Such treatment can be used to ensure better coupling of light from and into doped and undoped (active and non-active) portions of the finished zig-zag slab.

Fig. 8B illustrates another slab sandwich **90** in which index-matching layers **92** are interposed between active medium **94** and non-active media **96, 98.** Such treatment may be used to reduce reflection induced by an index difference between active medium **94** and non-active media **96, 98.**

In view of the above, it will be clear to one skilled in the art that the above embodiments may be altered in many ways without departing from the scope of the invention. Accordingly, the

scope of the invention should be determined by the following claims and their legal equivalents.